The New ICP Minimally Invasive Method Shows That the Monro–Kellie Doctrine Is Not Valid

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Abstract The Monro–Kellie doctrine states that the interior of the cranium is formed of three main components: blood, fluid and cerebral parenchyma. An increase in the volume of one or more components may increase the intracranial pressure (ICP). This doctrine also affirms that the skull cannot be expanded after the closure of the fontanels. Monro and Kellie's theory has been perfected during the last two centuries. This study leads to a new contribution that proves that even adults' consolidated skulls present volumetric changes as a consequence of ICP variations.

Keywords Intracranial pressure • ICP • Monro–Kellie • Medical instrumentation • Minimally invasive system • Monitor

Introduction

Alexander Monro, a professor of anatomy at the Edinburgh College of Medicine, has applied some of the principles of physics to intracranial content. Studying patients and corpses he concluded, in 1783 [1], that:

1. The brain was inside a bony structure (skull) that could not be expanded
2. The substance forming the brain was almost incompressible
3. Consequently, the blood volume inside the skull cavity was constant or almost constant, and a steady output of venous blood from the cranial cavity originated from a steady input of arterial blood.

Monro's hypothesis were supported by the experiences of his pupil George Kellie de Leith, a Scottish doctor who had carried out several studies on corpses and observed facts that made it possible to complete and correct some points of the theory proposed by his professor.

Kellie, with his observations, also postulated the following statements [2]:

1. The brain was enclosed and completely occupied a bone box that could not be expanded in adults
2. The brain presented low compressibility
3. It was unlikely that any fluid could be removed or that any excess could be introduced inside the cranial cavity without equivalent simultaneous changes in ICP

Occasional citations in the literature nominated this doctrine as the "Monro–Abercrombie doctrine" [3]. John Abercrombie was a pathologist working in the Edinburgh College of Medicine who made the same observations as Kellie carrying out total bleeding tests in animals [4] and supporting Monro's and Kellie's conclusions. This was fundamental to the hypothesis being accepted [5].

The discrediting by the scientific community was not surprising, as Galeno's idea, in the second century, that the cerebral ventricles were full of a "vital spirit," had survived for many centuries. François Magendie, a French physiologist, deserves the credit regarding the proof that fluid was present in the cerebral ventricles; he proved that these ventricles communicated with the subarachnoid space and the fourth ventricle through a ventricle that today bears his name [6].

The recognition of the cerebrospinal fluid (or liquor cerebrospinalis) as a vital component added another dimension to the cranial content equation, causing a profound effect on the understanding of intracranial pressure.

Cushing offered a precise formula for the Monro–Kellie doctrine and postulated that when the cranial box is intact, the sum of brain volumes of fluid and intracranial blood is constant. Consequently, an increase in one component must

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be compensated for by reduction of one of the other two [7]. Initially, the emphasis was directed to the intracranial pressure increase owing to its clinical implications. Intracranial hypotension, less severe and less common, was not initially taken into consideration.

In the original form, the hypothesis put forward by Monro and completed by Kellie had imperfections that were later corrected by other authors. What finally came to be known as the Monro–Kellie doctrine, or hypothesis, affirmed that the sum of the brain volumes of fluid and intracranial blood was constant. An increment in one of them must cause a reduction in one or in the other two intracranial components so that abnormalities do not occur. This hypothesis also implies that the cranial volume after closure of the fontanels is constant, that is, there is no cranial deformation in adults due to an increase or diminution of the intracranial components.

We have proved that it is possible to determine cranial deformations caused by internal pressure variations, and this implies that the Monro–Kellie doctrine is not strictly valid.

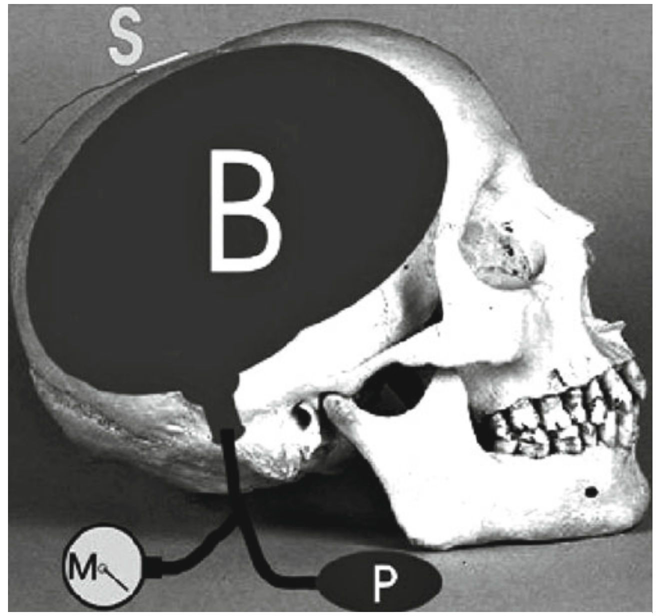

Fig. 1 System to measure bone deformation. *S* sensor; *B* balloon gas; *M* manometer, *P* pump air supply

Materials and Methods

"In Vitro" Experiments

In order to simulate the ICP changes, sensors of deformation (strain gauges) were applied to the parietal region of human skulls. The sensor was glued with ethyl-cyanoacrylate and connected to a monitoring system especially developed for the purpose.

To achieve this, the skull was filled with a rubber balloon connected to a bulb device to pump air and a manometer to determine the corresponding internal pressure (Fig. 1).

During the procedure the balloon was inflated in order to reach up to 100 mmHg internal pressure. The air valve was then opened and the system was continually monitored until the pressure returned to 0 mmHg.

The experiment was repeated five times. The data were stored in a computer and used in subsequent analyses.

"In Vivo" Experiments

Five 3-month-old male Wistar rats weighing between 270 and 300 g received our sensor in the right parietal bone. The animals were fixed by the legs on wooden supports with the ventral region tightly bound to the wooden surface.

The posterior region of the animals was elevated to 30°, 45°, and 90° for 30 s and the animal returned to the horizontal position (0°) for 5 min so that one maneuver did not interfere with the following. The tests were repeated three times in each animal. The same protocol was repeated elevating the anterior region of the animals.

Results

"In Vitro" Tests

Analyzing Fig. 2, one can observe that the sensor was able to capture the bone deformation provoked by an increase and decrease in the internal pressure. The chart contains the points that represent the average of the readings and the respective standard deviations.

The black squares represent the increased balloon pressure and the consequent cranial expansion. The sensor has shown sensitivity and reproducibility of results in all measurements as we can observe by the small standard deviation represented by the error bars.

The interpolated line through the points shows that the readings obtained are directly proportional to internal pressure. The gray points indicate the readings due to pressure reduction. The experiments have shown that the bone promptly responded to the internal pressure reduction, with no retardation or different values, to return to the initial readings; this has proved the non-existence of bone hysteresis, a fundamental rheological aspect that allows the quantitative validity of the method.

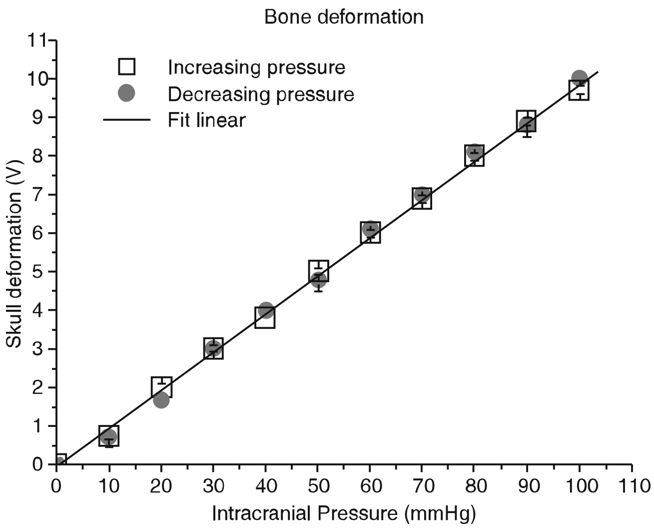

Fig. 2 Experiments in the skull. Hysteresis bone test. The *squares* represent the increase in internal pressure and the *circles* represent the decrease

"In Vivo" Tests

The ICP variation caused by postural maneuvers is also well known when this important physiological parameter is studied [7–11]. In hospitals, it is a common procedure to raise to 30° the head-rest of patients with intracranial hypertension [12]. When we raised the heads of patients or test animals, facilitation of the passage of the cerebrospinal fluid to the column occurred, reducing the volume of the fluid inside the skull and consequently reducing the ICP. Facilitation of the venous blood return also occurs, reducing the blood volume inside the skull and consequently reducing ICP.

The elevation of the posterior region of the animals produces exactly the opposite effect, as fluid migration into the skull occurs causing an ICP increase. This maneuver also contributes to the ICP variation as it diminishes the return of venous blood adding to the ICP increase.

Figure 3 shows the experimental results after elevation of the animal's posterior region in angles shown on the ordinate axis. Each symbol represents one animal and each point represents the average of three repetitions; the error bar on each point represents the standard deviation for each determination.

The 30° elevation of the animals' posterior region caused an ICP increase owing to fluid accumulation inside the skull and increased impedance to venous blood flow return. The same effect was observed with higher intensity when the animals were subjected to 45° and 90° inclinations.

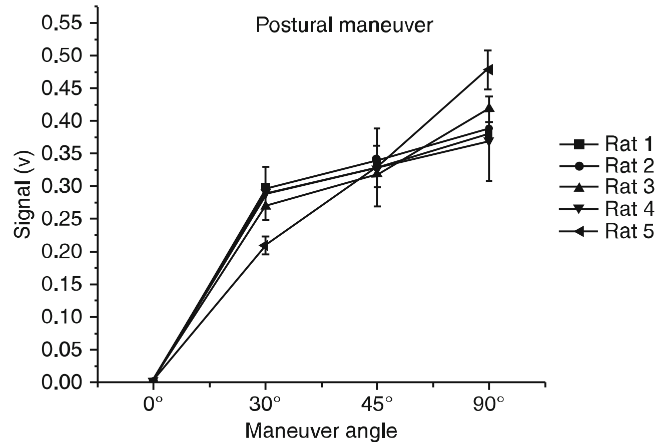

Fig. 3 Variation in the intracranial pressure through postural maneuvers. Elevation of the posterior region to increase intracranial pressure

Conclusion

1. Our proposed method shows that the hypothesis of an inextensible skull after the closure of the fontanels is not true.
2. The minimally invasive system to monitor the ICP detects the small changes (micrometers) in the skull volume.
3. Changes in the intracranial pressure lead to skull volume variations, we show this through in vitro and in vivo experimentations.
4. The relation between cranial deformation and internal pressure variation is linear, a fact that allows the minimally invasive method to monitor the ICP.

Conflict of interest statement We declare that we have no conflict of interest.

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